ADMESH: A Graphical User Interface for an Advanced Mesh Generator for Coastal Ocean Modeling

A Thesis

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By

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CHAPTER 1

INTRODUCTION

Recent extreme events, both natural and human-induced, that resulted in major detrimental consequences for coastal and low-lying areas (e.g., Hurricane Ike, the Tōhoku earthquake and tsunami, the Deepwater Horizon oil spill, etc), have demonstrated the severe vulnerability of coastal systems to these types of disasters and have highlighted the rising importance of effective coastal management and hazard mitigation strategies. Free surface flow and transport computer models are widely used to simulate and study a number of physical phenomena related to these types of events (e.g., tsunami waves, tides, hurricane storm surge, coastal ocean circulation, and the transport of sediment and pollutants); see, for example, [3, 4, 12, 8, 9, 10, 11, 27, 13].

One way in which these types of models are used is in the simulation of past disasters in order to learn valuable lessons that can be applied to provide protection against future events. For example, the ADvanced CIRCulation finite element model, ADCIRC [2, 27], is a computational tool that has been adopted operationally by numerous local, state and federal entities, including, for example, the U.S. Army Corps of Engineers, the Federal Emergency Management Agency (FEMA), the National Oceanic and Atmospheric Administration (NOAA), and the Louisiana State University Hurricane Center. The ADCIRC model was a crucial analysis tool in the aftermath of Hurricanes Katrina and Rita [4, 12] and is currently being used by FEMA to develop floodplain maps for Southern Louisiana and to study the recent Deepwater Horizon oil spill in the Gulf of Mexico [22].

One of the first steps in applying these types of computer models is the discretization, or creation of a computational mesh, of the physical domain of interest, e.g., the Gulf of Mexico or Lake Erie, see Figures 1.1 and 1.2, respectively. The creation of such a mesh is a very time-consuming and user-intensive process. Therefore, reducing the time and user involvement it takes to generate an unstructured mesh and to perform a simulation without compromising accuracy and quality would be very beneficial. By providing crucial information to emergency managers and first time responders quickly, preventative measures can be taken to reduce the wide variety of damaging affects caused by a disaster and to plan evacuation routes and clean-up efforts.

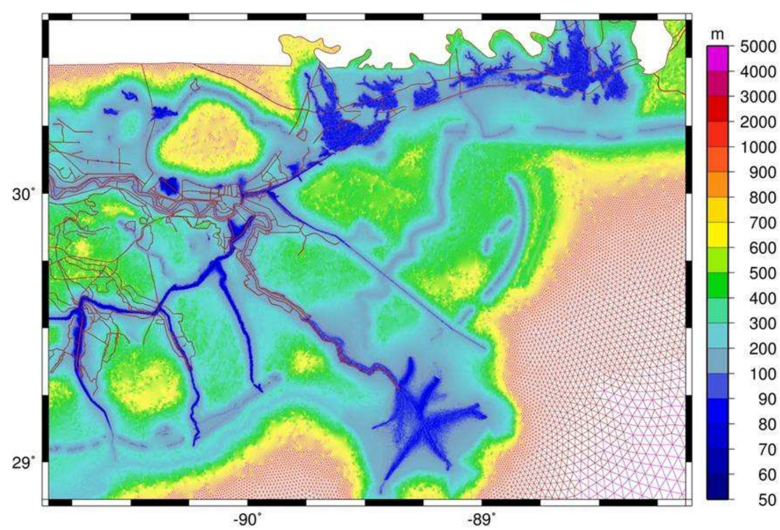


Figure 1.1: Example of an unstructured mesh of Southern Louisiana with varying finite element sizes shown in meters (m).

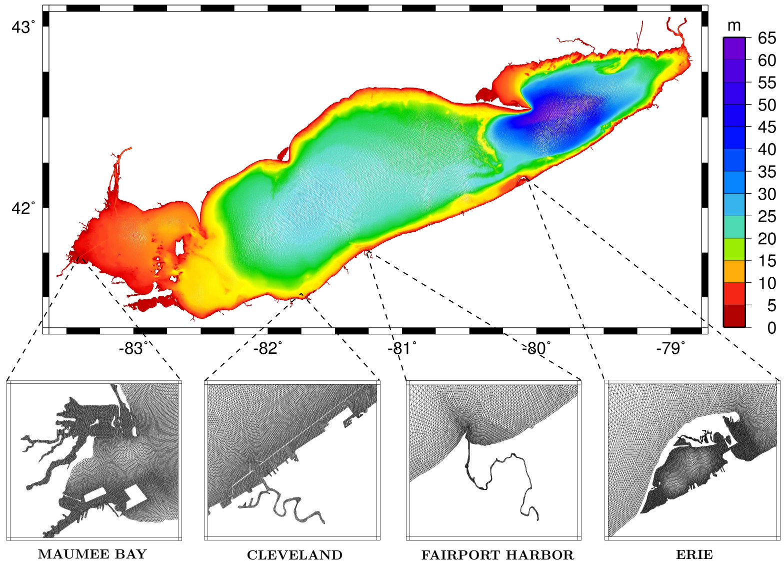


Figure 1.2: Example of an unstructured mesh of Lake Erie with varying finite element sizes shown in meters (m).

1.1 Motivation & Relevant Background

To address the challenge of minimizing the time in producing a high-quality computational mesh of a domain of interest, an *automatic* ADvanced unstructured MESH generator for free surface flow and transport models, called ADMESH [5], was created. ADMESH is a computational tool that is capable of automatically producing high-quality triangular meshes with minimal user input, such as the target element size, points defining the boundary and bathymetry/topography of the domain. The ADMESH program incorporates some the the latest and most advanced techniques recently developed in the area of mesh generation, as well novel approaches to incorporate factors that are specific to the problem of shallow water flow. Some of the techniques that are incorporated include the use of the so-called signed distance function, which is widely used in the context of level set methods, to determine critical geometric properties, the approximation of piecewise linear coastline data by smooth cubic splines, and a so-called mesh function used to determine element sizes and control the size ratio of neighboring elements.

The primary motivation for the research presented in this thesis is to address the challenge of minimizing the user-intensive process in creating a high-quality computational mesh by constructing an interactive Graphical User Interface (GUI) for the Admesh program, see Figure 3.1. Briefly, the Admesh GUI is implemented in Matlab and allows the user to view and edit input data and produce relevant output without requiring the additional knowledge of how the Ademsh program works. The GUI also contains an option to extract coastline data via the NOAA web-based coastline extractor database [20] to improve the efficiency in creating a computational mesh of a domain of interest at will.

1.2 Thesis Organization

This thesis is organized as follows. Chapter 2 provides a brief overview of the Admesh algorithm. Chapter 3 provides details of the construction and layout of the Admesh GUI. The function and purpose of the Admesh GUI features are then discussed, and images of the program features are provided. Chapter 4 provides results and example applications of the of the Admesh GUI, while Chapter 5 concludes with a discussion on future work for this project, and the challenges involved.

CHAPTER 2

A BRIEF OVERVIEW OF THE ADMESH ALGORITHM

This chapter provides a brief overview of the methods and algorithms employed by the ADMESH program.

2.1 Domain Representation

The first step in the ADMESH program is to read in a domain of interest $\Omega \subset \mathbb{R}^3$, which can be expressed as $\Omega = \Omega_{xy} \times z$, where $z(x, y)$ denotes the vertical elevation (bathymetric depth or topographic height) of a point $(x, y) \in \Omega_{xy}$. The boundary of Ω_{xy} is denoted by $\partial\Omega_{xy}$, which, along with z, is generally known at a discrete number of points obtained from, for example, coastline and bathymetric/topographic databases; see, for example, [20] and [21], respectively.

In ADMESH, the boundary $\partial\Omega_{xy}$ is loaded via a list of ordered points given in either geographic (latitude, longitude) or standard Cartesian coordinates. These points are automatically joined in ADMESH to form a closed polygon that represents the external boundary of the domain. Internal boundaries, e.g., islands or internal structures such as weirs, are also loaded via a list of ordered points and are joined to form closed polygons. The external boundary, along with internal boundaries are collectively referred to as an "edge structure" in ADMESH. The list of boundary points and resulting polygons are checked for various "inconsistencies" prior to meshing, e.g., the presence of double points, inconsistent direction among polygons, etc., which are corrected automatically in ADMESH. In addition to making use of this piecewise linear boundary representation, ADMESH also utilizes a smooth (twice differentiable) cubic spline approximation of the boundary, which allows for boundary curvature calculations to be performed as described in the next section. Similar to the boundary representation, the vertical extent of the domain z is loaded into ADMESH via a (generally non-uniformly spaced) set of data points, which can also be obtained from either an existing mesh of the domain or a separate bathymetric/topographic data set.

Given these boundary and bathymetric/topographic representations, discretization of the domain is essentially defined through the use of two discrete functions defined over a (structured) background mesh or grid that covers the entire extent of the domain. These two discrete functions are: (i) a signed distance function $\phi(\mathbf{x})$, which gives the shortest distance from a background grid point $\mathbf{x} = [x, y]$ to the boundary; and (ii) a bathymetry function $B(\mathbf{x})$, which gives the corresponding bathymetric depth of the point (without loss of generality, this is referred to as a bathymetry function in ADMESH, though it would also describe topographic height for portions of the domain that cover land). As described in the next section, a number of related functions and quantities that play an important role in controlling the mesh sizes h throughout the domain are computed from these two discrete functions.

2.2 Mesh Resolution

The use of unstructured meshes in shallow water modeling has been shown to be an efficient way to obtain highly accurate numerical solutions with minimal computational effort; see, for example, [26], [14]. This efficiency is a direct result of the ability of unstructured meshes to easily provide varying spatial resolution throughout the domain. Providing a means by which appropriate mesh resolution or element sizes are automatically prescribed in different parts of the domain — based on various physical and geometric factors discussed below — is a critical part of the automatic mesh generation process. ADMESH employs the basic mesh size function technique proposed by Persson [25] with additional modifications made to incorporate factors that are specific to the problem of shallow water flow. This technique is described briefly below.

In ADMESH, initial mesh sizes $h_0(\mathbf{x})$ are based on the following criteria:

1. **Shoreline curvature**: It is important that the geometric complexity of natural shorelines is adequately represented in shallow water models. This is accomplished in ADMESH by controlling mesh resolution based on shoreline curvature. Given a boundary as described in section 2.1, the curvature $\kappa(\mathbf{x})$ is calculated from a smooth cubic spline approximation of the boundary using standard formula; see, for example, [19]. ADMESH requires that

$$h_0(\mathbf{x}) \;\leq\; \frac{1}{K\,|\kappa(\mathbf{x})|}, \tag{2.1}$$

where K is the number of elements per radian as specified by the user. See, for example, Figure 2.1. Based on generating a number of meshes using real shoreline data, it has been determined that $K = 15$ to 25 seems to be a reasonable range for this parameter. This mesh size criterion based on curvature is set to only affect a narrow band of background nodes surrounding the boundary by effectively setting $K = 0$ outside of this band.

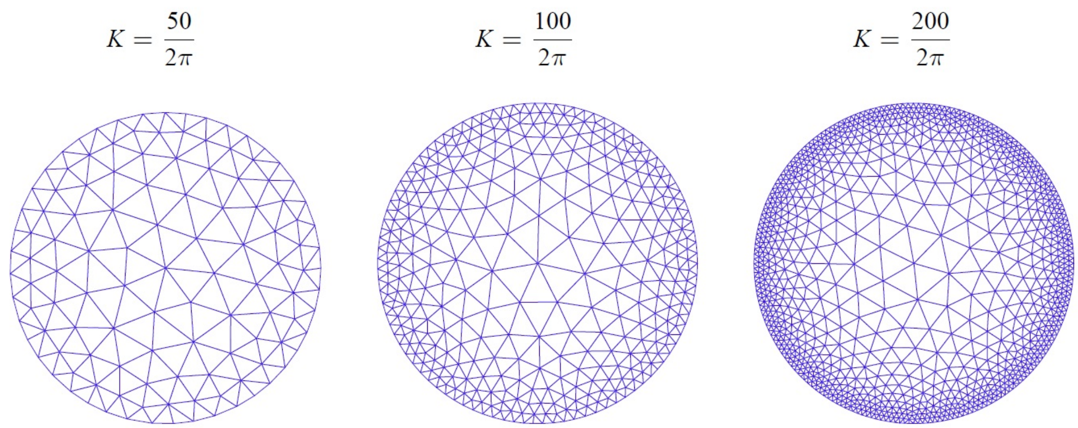


Figure 2.1: Sample images of various values for curvature.

2. **Local feature size**: Adequate resolution of channels/tributaries in shallow water domains is noted in [7] to be critical in obtaining valid solutions, especially for transport problems. ADMESH ensures this requirement is met through the use of a local feature size mesh adaptation that controls the minimum number of elements that span the channels/tributaries. In particular, ADMESH requires that

$$h_0(\mathbf{x}) \;\leq\; \frac{\mathrm{lfs}(\mathbf{x})}{R}, \tag{2.2}$$

where the local feature size $\mathrm{lfs}(\mathbf{x})$ is approximately half the width of the channel/tributary at a point $\mathbf{x}$. The parameter R sets the minimum number of elements that span half of the channel/tributary, e.g., if $R = 1$ then a minimum of 2 elements will span any channel/tributary within the domain. See, for example, Figure 2.2.

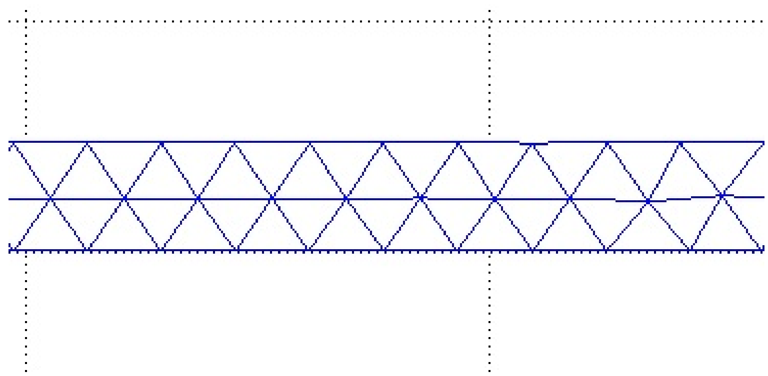


Figure 2.2: Snapshot of a channel in an ADMESH test case where the local feature size parameter R is set equal to 1.

3. **Bathymetry gradients**: To ensure adequate resolution is used in the domain to capture changing bathymetry, as suggested in [29], ADMESH requires that

$$h_0(\mathbf{x}) \;\leq\; s\left|\frac{\nabla B(\mathbf{x})}{B(\mathbf{x})}\right|^{-1}, \tag{2.3}$$

where s is a user specified parameter (taken to be in the range $s = 0.05$–0.30 in [29]).

4. **Tidal wavelengths**: Assuming tidal waves propagate at their linear shallow water wave speeds c, i.e., $c = \lambda/T = \sqrt{gB}$, where λ is the tidal wavelength, T is the wave period, and g is the acceleration of gravity, ADMESH requires that

$$h_0(\mathbf{x}) \;\leq\; \frac{\lambda}{C}, \tag{2.4}$$

to guarantee that proper resolution is used to capture the flow characteristics. In (2.4), C is the number of elements per wavelength as specified by the user.

5. **Minimum and maximum resolution**: Finally, the user can explicitly specify minimum and maximum element sizes h_{min} and h_{max}, respectively, between which all element sizes of the initial mesh must fall, i.e.,

$$h_{min} \ \leq \ h_0(\mathbf{x}) \ \leq \ h_{max}. \tag{2.5}$$

From an initial mesh size function $h_0(\mathbf{x})$ designed to meet requirements (2.1)–(2.5) (or some subset of them), a final mesh size function $h(\mathbf{x})$ is obtained and designed to meet an additional "grading" requirement. Specifically, ADMESH requires that the ratio of neighboring element sizes is less than a factor G (specified by the user). In a continuous setting, this can be expressed as

$$\nabla h(\mathbf{x}) \ \leq \ g \approx G - 1. \tag{2.6}$$

This condition can be met by seeking a steady state solution to the so-called gradient limiting equation,

$$\frac{\partial h}{\partial t} + |\nabla h| = \min\left(|\nabla h|, g\right) \tag{2.7}$$

with an initial condition

$$h(\mathbf{x}, t = 0) \ = \ h_0(\mathbf{x}). \tag{2.8}$$

Note that at steady state ($\partial h/\partial t = 0$), equation (2.7) reduces to $|\nabla h| = \min\left(|\nabla h|, g\right)$, which is equivalent to condition (2.6).

In ADMESH, any of the above arguments (2.1)–(2.6) can be turned on or off when running ADMESH.

2.3 Mesh Generation

Given the domain representation and the mesh size function as described above, a mesh is generated for a given domain by first performing a Delaunay triangulation of an initial set of mesh nodes that has a density proportional to $1/h(\mathbf{x})^2$; i.e., more nodes are placed in areas requiring high mesh resolution (small h) as prescribed by the mesh size function. The quality of this initial mesh is then refined iteratively by making use of some simple concepts from spring mechanics as described briefly below.

The basic idea is to model each element edge of the mesh as a spring with, for example, a force of the form $f = k(l_h - l_i)$, where k is a spring constant, l_i is the length of the element edge in the current triangulation T_i, and l_h is the desired length as prescribed by the mesh size function. A sum of spring forces is then taken around each mesh node, and force equilibrium is sought by allowing mesh nodes to be repositioned *and* by allowing the mesh topology to change through re-triangulation until the entire spring system (i.e., the entire mesh) is in equilibrium (to within a prescribed tolerance). Following the methodology of [23], if a mesh node moves outside of the domain (as determined by the sign of the distance function) while solving for equilibrium, it is "pushed" back to the closest point on the boundary using the gradient of the distance function. Figure 2.3 shows a mesh generated using this approach, where both the initial Delaunay triangulation of the domain and the final mesh obtained from force equilibrium are shown. As demonstrated in the next section, this approach produces very high-quality meshes with respect to certain mesh quality measures.

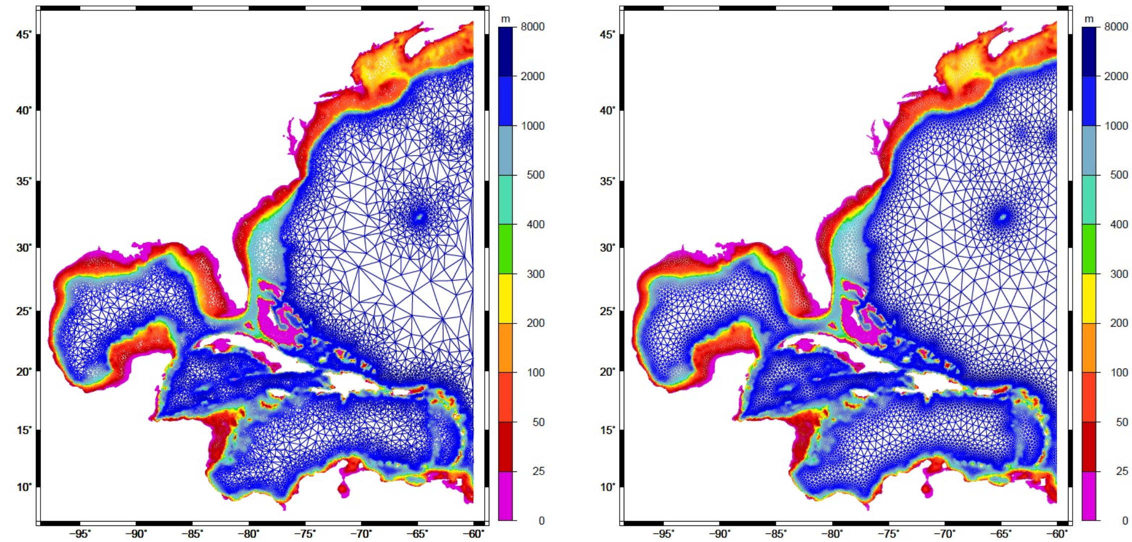


Figure 2.3: A mesh of the Western North Atlantic, Gulf of Mexico, and Caribbean Sea created using ADMESH showing the initial Delaunay triangulation of the domain (left) and the final mesh obtained from force equilibrium (right). Colors indicate bathymetric depths.

2.4 Mesh Quality

Upon completing the mesh generation, ADMESH performs a mesh quality check. ADMESH measures the mesh quality by using twice the ratio of the radius of the largest circle contained in the triangular element r_{i} (the so-called incircle or inscribed circle of the triangle) and the radius of circumscribed circle of the triangle r_{o}, i.e.,

$$q = 2\left(\frac{r_{\mathrm{i}}}{r_{\mathrm{o}}}\right) = \frac{(b+c-a)\,(c+a-b)\,(a+b-c)}{abc}$$

where a, b, and c, are the edge lengths of the triangular element. Note this measure gives a value of $q = 1$ for an equilateral triangle and $q = 0$ for a completely degenerate triangle. This measure is illustrated graphically in Figure 2.4.

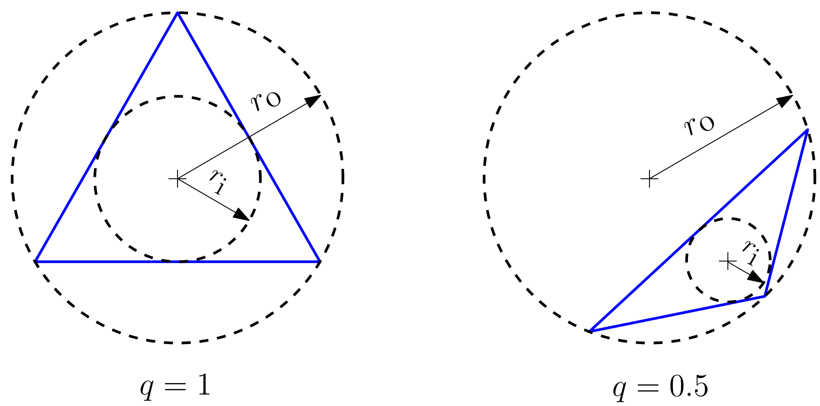


Figure 2.4: Geometric depiction of the element quality measure used to assess mesh quality.

It is desirable to have a mesh composed of nearly equilateral triangles when using finite element methods because upper bounds on errors generally depend on the smallest angle in the mesh, and good numerical results are usually obtained for elements whose angles are close to 60 degrees [6]. As a “rule of thumb” noted in [24], generally if all triangles have a $q > 0.5$, then the mesh is considered “good”. Here, we report a single value Q of mesh quality for a given mesh, which we take as the average of all q of the mesh. Typically, meshes created with ADMESH have a mean element quality measure of $Q \geq 0.90$, with some examples presented in later chapters as high as $Q = 0.97$.

CHAPTER 3

CONSTRUCTION & IMPLEMENTATION OF THE ADMESH GUI

This chapter provides the basic information required to describe the construction and implementation of the ADMESH GUI.

3.1 Constructing the ADMESH GUI

The ADMESH program is currently coded in MATLAB; Therefore constructing the ADMESH GUI utilizing MATLAB's graphical user interface design environment, (GUIDE) [16], was a natural progression for this project. GUIDE provides the necessary tools needed to create and edit a GUI and incorporate program functions that make the GUI work. MATLAB also compiles and builds standalone applications that would allow users that do not have MATLAB, or have experience with MATLAB, to use the ADMESH GUI.

At the beginning phase of designing the ADMESH GUI, the objective of the design and layout was to provide program features that would minimize work by the user at each major step of the mesh generation process. The major steps considered were

- Providing an edge structure to model, either by loading an existing domain or creating a new domain.

- Automatically generating a computational mesh with minimal user input and displaying the relevant output.

- Performing element quality checks and providing feedback on element quality.

- Saving the results in a format readable by ADCIRC for modeling.

The framework of the GUI was constructed taking these factors into consideration. After many upgrades and design and layout adjustments, the final constructed ADMESH GUI is displayed in Figure 3.1. The following is a list of the of GUI components, corresponding to the numbers labeled in Figure 3.1, and a brief description of their function.

1. *NOAA Coastline Extractor*: This button opens the online NOAA coastline extractor to allow the user to select a coastline.

2. *Select Existing Edge Structure*: This button allows the user to upload an existing edge structure.

3. *Select Existing ADCIRC Mesh*: This button allows the user to upload an existing ADCIRC mesh.

4. *Variable Input & Selection*: Allows the user to define maximum and minimum element sizes, dominate tide, mesh grading factor, curvature of the element, local feature size, option for including bathymetry data, and the option to save the final mesh as a figure.

5. *Plot & Video Window*: Allows the user to view their domain prior to mesh generation. This window also displays the formation of the triangular elements as the ADMESH program is running.

⑥ *Program Tracking*: The text string informs the user of what functions are being performed by ADMESH and provides progress completion in percentages.

⑦ *Run ADMESH*: Following selection of the edge structure and variable settings, the "Run ADMESH" button starts the program.

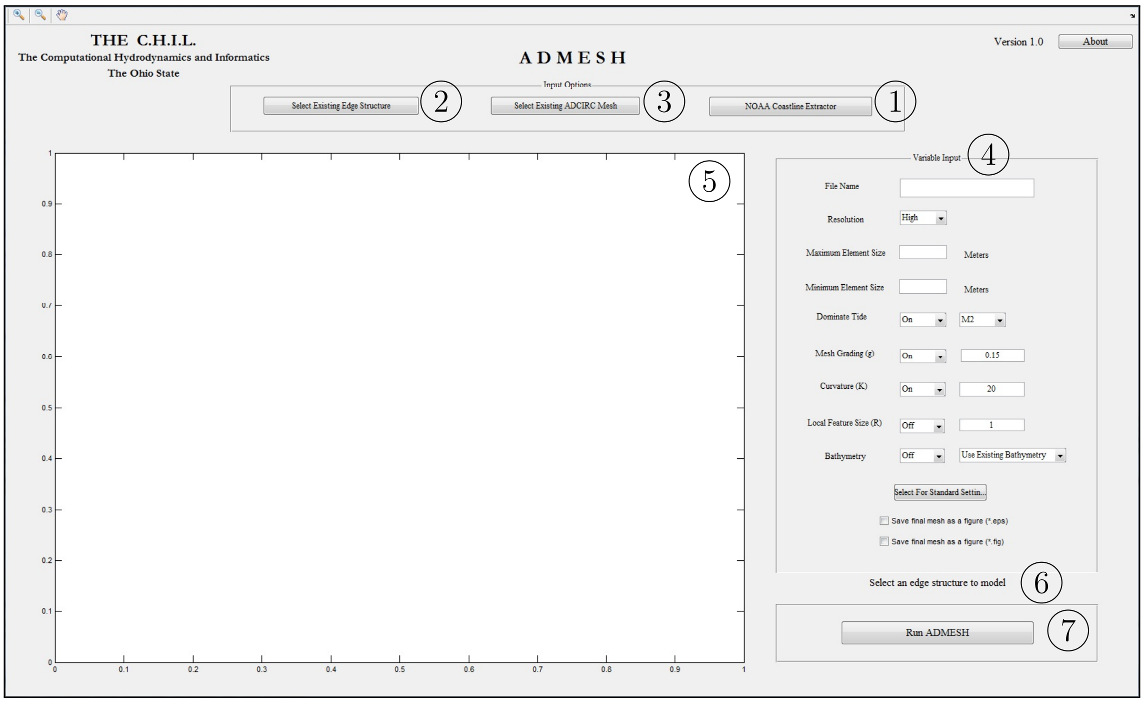


Figure 3.1: ADMESH Graphical User Interface.

The following provides details of the ADMESH GUI features and how these functions are used and implemented by a user.

3.2 Program Features and Implementation

Prior to the implementing ADMESH into a GUI, the program fulfilled the challenges of automatically generating a computational mesh, performing element quality checks and saving the results in a format readable by ADCIRC for modeling. However, one of the first steps in creating a computational mesh using ADMESH is providing a closed domain, or edge structure to model. Obtaining Cartesian or geographic latitude and longitude data for a particular domain of interest can be challenging and time consuming. Therefore, the first phase in the development of the ADMESH GUI was developing a method for allowing the user to choose a domain of interest in the ADMESH GUI.

3.2.1 Selecting the Input Data

In the ADMESH GUI, there are currently three options for loading an edge structure. The following provides details on each option.

NOAA Coastline Extractor

NOAA provides an online coastline extractor that allows a user to select a coastline of their choice and provides coastal format options for downloading geographic latitude and longitude data (GMT ASCII, Arc/Info Ungenerate, MATLAB, Splus and Mapgen). Incorporating this tool into the ADMESH GUI is very beneficial to the user due to the time involved in creating a domain. One current technique for creating readable ADMESH and ADCIRC coastlines is tracing coastlines from satellite imagery — a process that can take weeks, potentially months depending on the size of the domain. The NOAA Coastline Extractor tool is utilized by ADMESH to allow the user to select their domain of interest with minimal user involvement.

When a coastline is selected using the NOAA Coastline Extractor, the data, in MATLAB format, is provided in two column vectors on a web page. The first column represents latitude data and the second column represents longitude data. Different segments of the data set are separated by nan's; see, for example, Figure 3.2. The benefit of this separation is that the latitude and longitude data set is in order between each "nan", however the NOAA Coastline Extractor separates segments of coastlines such that segments of coastline data may represent whole islands or they may only represent parts of an island or the mainland.

```
nan nan
-70.072683      41.869886
-70.07327       41.870472
-70.074443      41.871059
-70.075617      41.872232
-70.077084      41.873112
-70.078257      41.873992
-70.080604      41.874286
-70.081484      41.874579
-70.082364      41.874579
-70.082951      41.874286
-70.083244      41.872232
-70.082364      41.871352
-70.080604      41.870472
-70.07943       41.869592
-70.077377      41.868419
-70.07503       41.868125
-70.073857      41.867539
-70.072683      41.867832
-70.072683      41.869886
nan nan
-70.344036      41.719101
-70.343156      41.718808
-70.342569      41.717928
-70.343743      41.715288
-70.344036      41.715288
-70.346383      41.716461
-70.346676      41.717928
-70.345796      41.718515
-70.344916      41.718515
-70.344036      41.719101
nan nan
```

Figure 3.2: Sample data det from Cape Cod Bay coastline extraction using the NOAA Coastline Extractor.

To use the coastline data provided by the coastline extractor as is, the user would need to go through the tedious process of manually sorting the coastline data. The ADMESH GUI addresses this issue by having the user copy and paste the URL containing the coastline data into a dialogue box. The user then selects an "OK" button and ADMESH downloads the data and implements an algorithm that compares starting and ending points of each segment with one another and combines separated segments. The ADMESH program utilizes 3-D arrays to store the complete coastline data set into one variable, while keeping the mainland and each island included in the coastline extraction separate and organized.

A requirement for ADMESH to properly generate a computational mesh is that the edge structure be a closed boundary. Therefore the beginning latitude and longitude values should match the last latitude and longitude values in a vector, indicating a closed boundary. Prior to running ADMESH using an existing edge structure, the program will perform this check and inform the user if any of the boundaries within their file are incomplete. When using the NOAA Coastline Extractor, a coastline may be selected by the user that does not have the same beginning and ending coordinates. This issue is addressed by allowing the user to define the remaining boundary parameters during the coastline extraction process.

The NOAA Coastline Extractor in ADMESH asks the user to select one of two options after downloading their coastline data,

- Option 1: Selected if the user chose a coastline where all boundaries are complete.
- Option 2: Selected if the user chose a coastline where one boundary is incomplete.

If Option 1 is selected, the program will sort and separate all coastlines, convert the data set to Cartesian coordinates, and allow the user to save their coastline data in a MATLAB (.mat) file and a mesh (.14) file to be used by ADCIRC.

If Option 2 is selected, the program will sort and separate all coastlines and upon completion will allow the user to input latitude and longitude coordinates to close in the mainland edge structure. See for example, Figure 3.3.

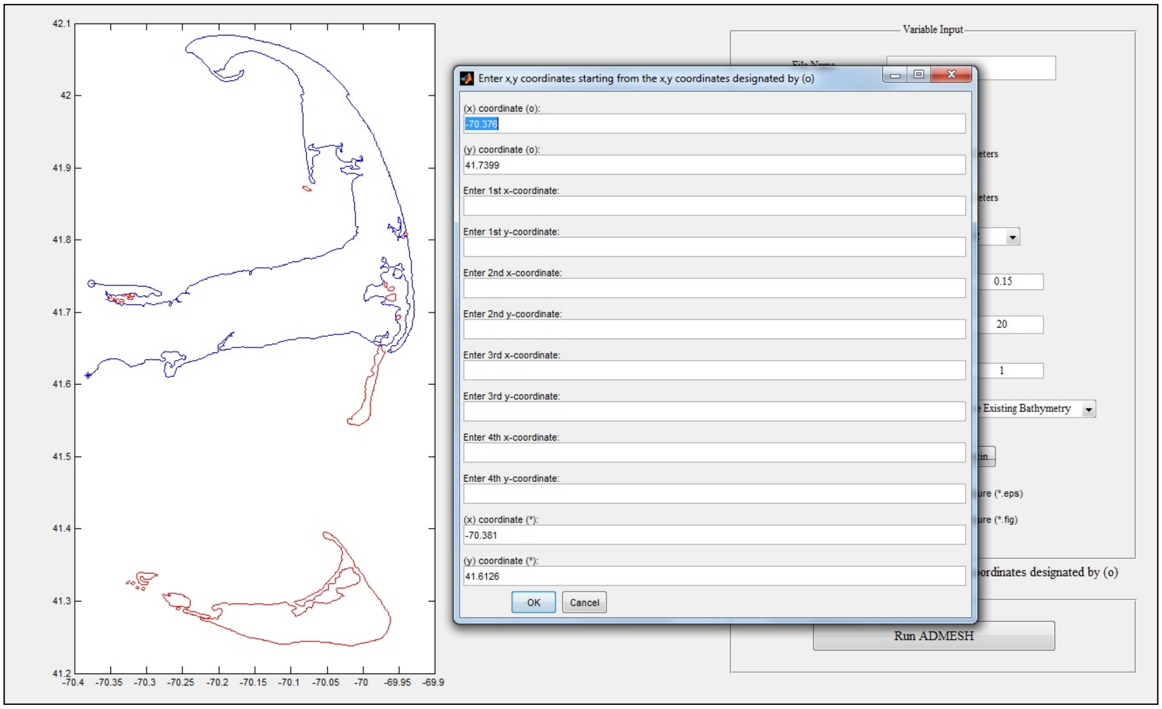


Figure 3.3: Example of a user defined coordinate input to close in the coastline of Cape Cod Bay.

After the user inputs a bounding box, ADMESH will display a preview of the complete coastline and give the user the option to change their coordinates if needed. Following confirmation by the user, ADMESH will convert the data set to Cartesian coordinates and save the coastline data in a MATLAB (.mat) file and a mesh (.14) file to be used by ADCIRC. See Figure 3.4 for an example of a completed coastline extraction.

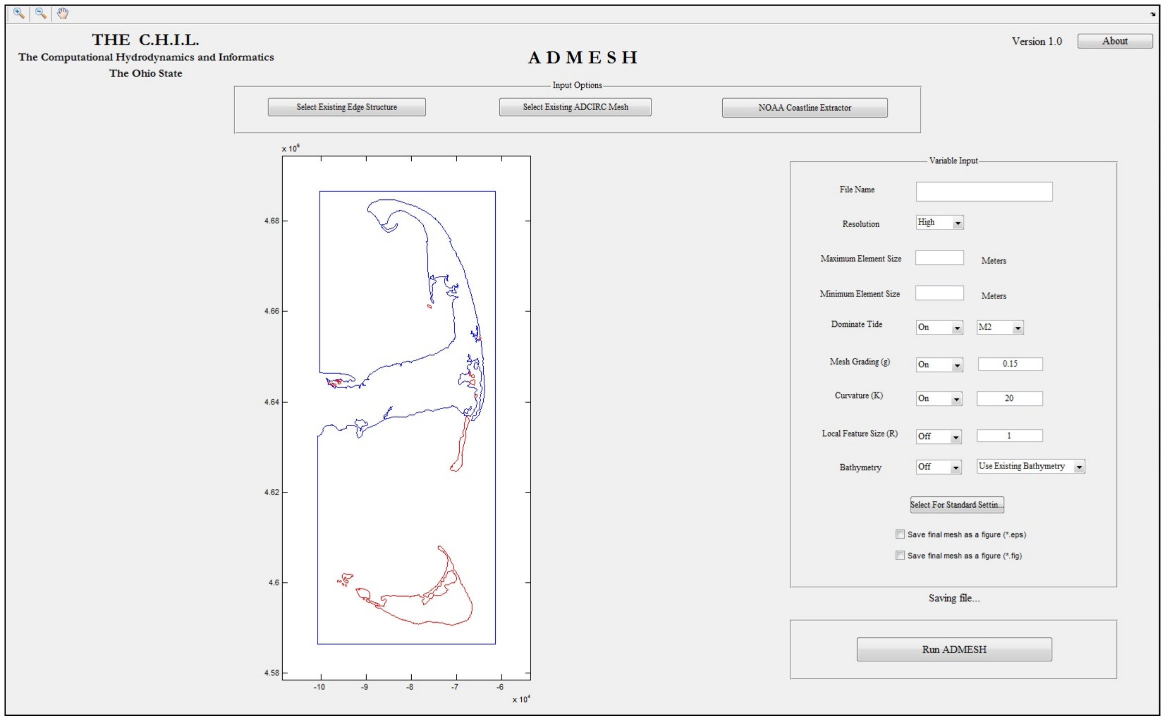


Figure 3.4: Example of a completed user defined coordinate input coastline of Cape Cod Bay.

Selecting an Existing Edge Structure

In the Admesh GUI, the user is able to download a variety of boundaries to use with the NOAA Coastline Extractor. The user can then upload their edge structure by simply selecting the "Selecting an Existing Edge Structure" button which will open a modal dialog box that lists files in the current Matlab directory. The benefit of a modal dialog box is that the user can select a file in any directory of their choice and not be confined to Matlab's current directory as is normally the case when programming in Matlab. The modal dialog box is used by all open and save functions in the GUI so that the user can open and save files in any directory.

Selecting an Existing ADCIRC Mesh

The user is also able to upload an existing ADCIRC mesh by selecting the "Select Existing ADCIRC Mesh" button. These files contain the ADCIRC .14 extension used for mesh files. The GUI reads in the data contained in the file and through a series of dialogue boxes asks the user (i) if the data is in Cartesian or Geographic coordinates, (ii) if bathymetry is included in the file, and (iii) if the user wants to save their converted edge structure in a MATLAB (.mat) format.

Following selection of one of the previous two options the user will see a preview of their coastline in the viewing window and will then go on to entering and selecting the appropriate values under the variable input.

3.2.2 User Variable Input

The variable input section of the GUI allows the user to select settings to be used by ADMESH for generating a computational mesh. Figure 3.5 shows the variable input section of the GUI, and the following discussion provides a brief description of how each feature works numbered 1-10 in Figure 3.5. See Chapter 2 and [5] for a more detailed explanation of roles of these variables in the ADMESH program.

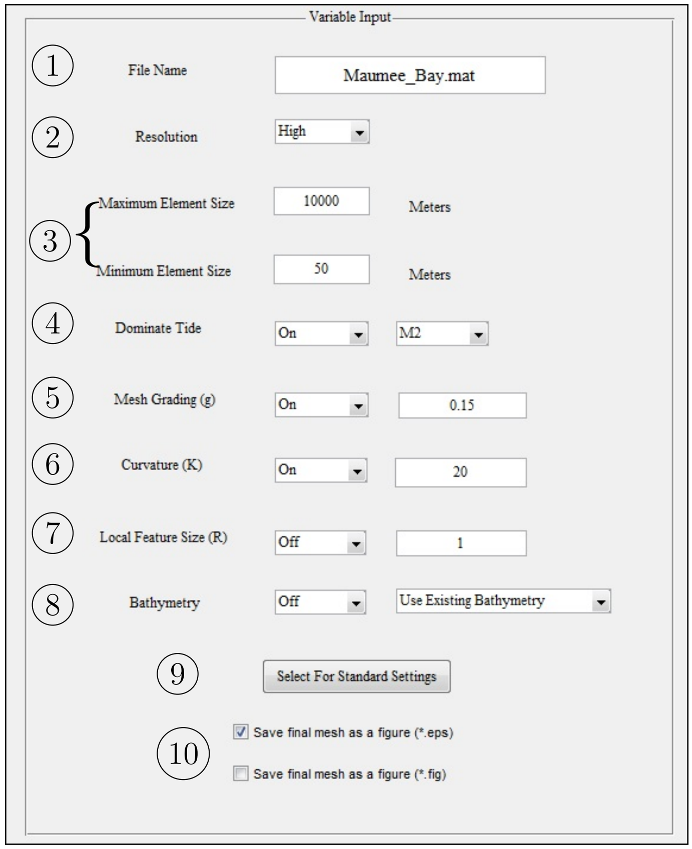


Figure 3.5: Variable Input Section of the ADMESH GUI.

(1) *File Name*: The file name text box is populated by the GUI coding when a user selects an edge structure by using the "Select Existing Edge Structure" button, "Select Existing ADCIRC Mesh" button, or upon completion of downloading a coastline using the NOAA Coastline Extractor. The GUI will not properly load an edge structure if the file name is typed into the text box because a file directory is required in order for the GUI to upload the correct file.

(2) *Resolution*: This variable is used by ADMESH when determining the background grid resolution, one of the first steps in the automatic mesh generation process.

A pop-up menu is used to allow the user to set the background grid resolution at a high, medium, or low setting that correspond to predetermined values in the ADMESH program.

3. *Maximum and Minimum Element Sizes*: The maximum and minimum element sizes, determined by the user, are entered into the GUI in units of meters. These values are used in a mesh function that determines the mesh resolution throughout the domain. These values will vary depending on the domain.

4. *Dominate Tide*: The dominate tide is used in the ADMESH program to resolve flow characteristics in the deep ocean where tides have a major affect. The user is able to use the pop-up menu to turn this feature on or off and is provided an additional pop-up menu with four of the major semi-diurnal tidal constituents, M_2, S_2, N_2 and K_2. These variables are associated with a value within the ADMESH program that determines element size based on proper resolution of the associated tidal wavelength.

5. *Mesh Grading*: The mesh grading is used in the ADMESH program as a tolerance for the difference in sizes between neighboring elements. The user is able to use the pop-up menu to turn this feature on or off and can prescribe the tolerance of the ratio between neighboring elements. Currently, the range 0.15 to 0.25 is used in ADMESH. When the GUI is initially opened, the value 0.15 is already input in the corresponding text box.

6. *Curvature*: Curvature, K, is used in ADMESH to establish the number of elements per radian in 2D; see Figure 2.1 for example. This value is used in

calculating the curvature of the boundary and establishing the shoreline adaptation of the elements. The typical value used in ADMESH is $K = 20$. The user is able to use the pop-up menu to turn this feature on or off and can edit the curvature value in the corresponding text box.

7 *Local Feature Size*: The local feature size is a value used in ADMESH to control the number of elements that span half of the channels/tributaries in a domain. For example, if the value is set at 1, there will be a minimum of 2 elements spanning the width of any channels/tributaries; see for example, Figure 2.2. The typical value used in ADMESH is 1. The user is able to use the pop-up menu to turn this feature on or off and can edit the local feature size value in the corresponding text box.

8 *Bathymetry*: Bathymetry is used in AMESH to capture fluid flow characteristics that are affected by bathymetric gradients inside the domain. Bathymetry in ADMESH can be uploaded in one of two ways, the user can have bathymetry data included in a MATLAB file assigned to the variable "bathy", or the user can choose to upload a separate .xyz file. The user is able to use the pop-up menu to turn this feature on or off and can use the corresponding pop-up menu to select whether the bathymetry data loaded is included in the edge structure file or in a separate .xyz file.

9 *Standard Settings Button*: The standard settings button was included in the ADMESH GUI to take into consideration new users experimenting with settings that would like to revert back to settings that work for most domains. When this button is selected, the resolution is set to "high", the maximum and minimum

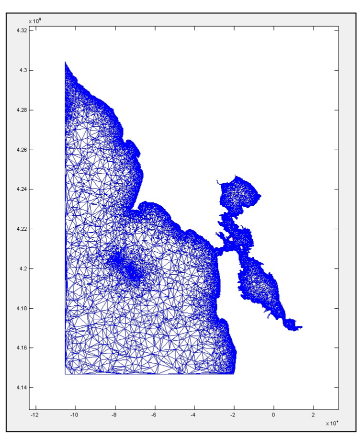
element sizes are cleared, the dominate tide is turned "on" and set to "M_2", the curvature is turned "on" and set to 20, the local feature size is turned "off" and bathymetry is turned "off". All the user is required to do at this point is input maximum and minimum element sizes to the run ADMESH.

(10) *Mesh Image Saving Features*: Prior to running ADMESH, the user can choose to save a figure of the completed mesh in a .eps and/or a .fig file. This feature was included for documenting final results.

3.2.3 Plot & Video Features

One of the main features incorporated into the ADMESH GUI is the viewing window. It is here that the user can view their edge structure prior to running ADMESH, when using the NOAA Coastline Extractor (see Figures 3.3 and 3.4), while running ADMESH, and upon completion of the ADMESH program.

Below are sample images taken during a test run of the San Francisco Bay.



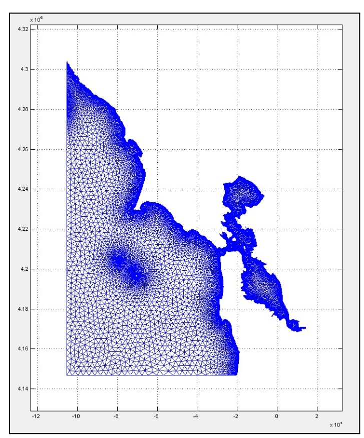


Figure 3.6: A mesh of the San Fransisco Bay created using Admesh showing the initial Delaunay triangulation of the domain (left) and the final mesh obtained from force equilibrium (right).

3.2.4 Preventing User and Edge Structure Errors

After the user has uploaded an edge structure to be modeled and has set the variables in the variable input section of the GUI, they can then select the "Run Admesh" button. At this point, the GUI uses the settings from the variable input and assigns the given values and variables appropriately. However, in the case of user error, such as leaving the maximum and minimum element fields blank or turning "on" the bathymetry setting with no bathymetry data, the GUI is coded to warn the user of these errors using pop-up dialogue warning boxes and stops the program from running and re-sets itself. The GUI was coded such that it would be operational without requiring Matlab to display programming errors in the Matlab command window.

Following these user error checks, the next step in the Admesh program is to check the edge structure for proper orientation. In order for Admesh to run properly, the coordinates of each edge structure (mainland and islands) must be going clockwise. The *Surveyor's Area Formula* [1] is used in the Admesh program to determine the edge structure orientation. For example, consider the generic domain shown in Figure 3.7. The *Surveyor's Area Formula* is used by first choosing the left most coordinate point in the edge structure, and assigning these coordinates as (x_B, y_B). The coordinates just before and just after (x_B, y_B) in the edge structure list are assigned to (x_A, y_A) and (x_C, y_C), respectively.

The following equation is then used to determine the area.

$$A = \frac{1}{2}[(x_A - x_C)(y_B - y_A) - (x_A - x_B)(y_C - y_A)] \tag{3.1}$$

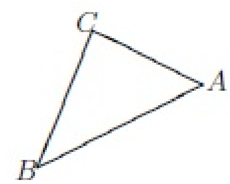


Figure 3.7: Generic domain for demonstrating the *Surveyor's Area Formula*.

If the coordinates are going in a clockwise direction, then the expression above will result in a negative value. If the coordinates are going in a counterclockwise direction, then the expression above will result in a positive value and in this case the program will automatically reverse that edge structure.

3.2.5 Running ADMESH & the Program Tracker

Following these initial error checks, the ADMESH program will begin evaluating a series of distance functions and mesh size functions and finally begin automatically producing a computational mesh. Once the ADMESH program has completed the mesh, the user can save their output to an ADCIRC readable mesh (.14 file) and depending on the users selection, save figures of the output as well.

Throughout this process, following the user selecting the "Run ADMESH" button, text above the button informs the user of the status of the program at each step of the mesh generation process; see Figure 3.1 on page 16. Upon completing the required distance and mesh size functions, the program tracker will display the completion of the meshing process in percent; see, for example, Figure 3.8. Following completion of the mesh the program tracker will display the time taken to complete with appropriate units (e.g., 30.36 seconds or 5 hours 20 minutes 36 seconds), the minimum element quality and the average mesh quality. Element quality checks are important in a mesh because numerical results from the computational mesh are better when elements are close to equilateral triangles as discussed in Chapter 2.4.

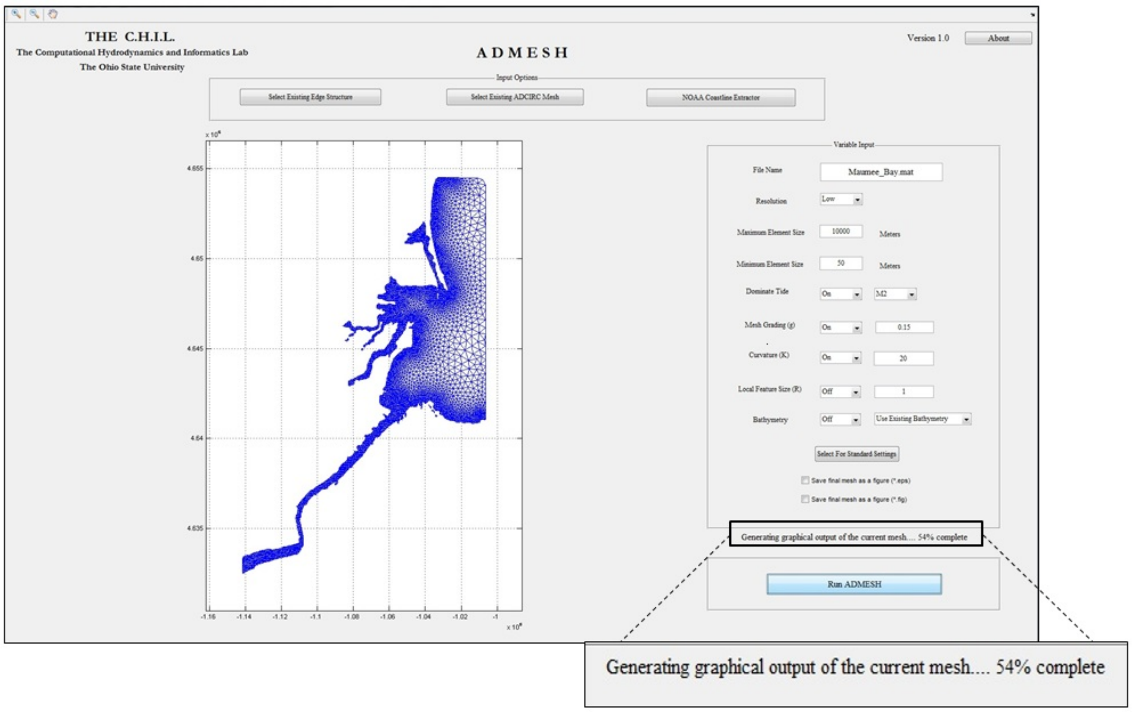


Figure 3.8: Snap shot of ADMESH generating a mesh of Maumee Bay at 54% completion.

CHAPTER 4

EXAMPLE HYDRODYNAMIC MESHES

In this chapter, computational meshes of several domains created with ADMESH are presented. In each example, coastline data was obtained using either NOAA's online coastline extractor tool or using an existing ADCIRC mesh. Each mesh was generated on a 64-bit DELL Optiplex 990 machine with 12 GB RAM and dual quad-core 3.40 GHz Intel i7-2600 processors. Examples of meshes including bathymetry are first presented followed by examples of meshes without bathymetry. A summary of the meshes generated using ADMESH are presented in Table 4.1. For the following examples, the dominate tide was set to M_2 and the local feature size was turned "off".

Table 4.1: Summary of the meshes generated with ADMESH.

Domain	No. nodes	Run time (hrs)	Max. element size (km)	Min. element size (m)	Mesh quality
WNAT	49,916	0.35	200	5000	0.9699
Gulf of Mexico	134,076	7.04	50	200	0.9711
Cape Cod	151,925	2.40	2	25	0.9723
Italy	13,011	0.15	100	2500	0.9287

The following subsections show figures of completed meshes along with figures displaying the operation of the ADMESH GUI during a run.

4.1 WNAT

The Western North Atlantic tidal (WNAT) domain [28] is an example of a domain that has been used in hurricane storm surge propagation studies; see, for example, [4] [28]. The WNAT domain consists of South, Central, and North American coastlines and has an open ocean boundary that includes the Gulf of Mexico and the Caribbean Sea. This domain was uploaded to ADMESH from an existing ADCIRC mesh that includes bathymetry. An unstructured mesh was generated with this boundary using a resolution set to Low, a maximum element size of 200 km, a minimum element size of 5 km, a mesh grading factor of 0.20, and a curvature of 15. With these inputs, the resultant mesh would not be adequate for hurricane storm surge predictions because greater resolution is needed near the coastline. However, it would be sufficient for tidal simulations. ADMESH completed the mesh in approximately 21 minutes and this example has an average mesh quality of 0.97.

Figure 4.3 shows the edge structure prior to running ADMESH. The figures that follow show the initial Delaunay triangulation of the domain and the final mesh obtained from force equilibrium.

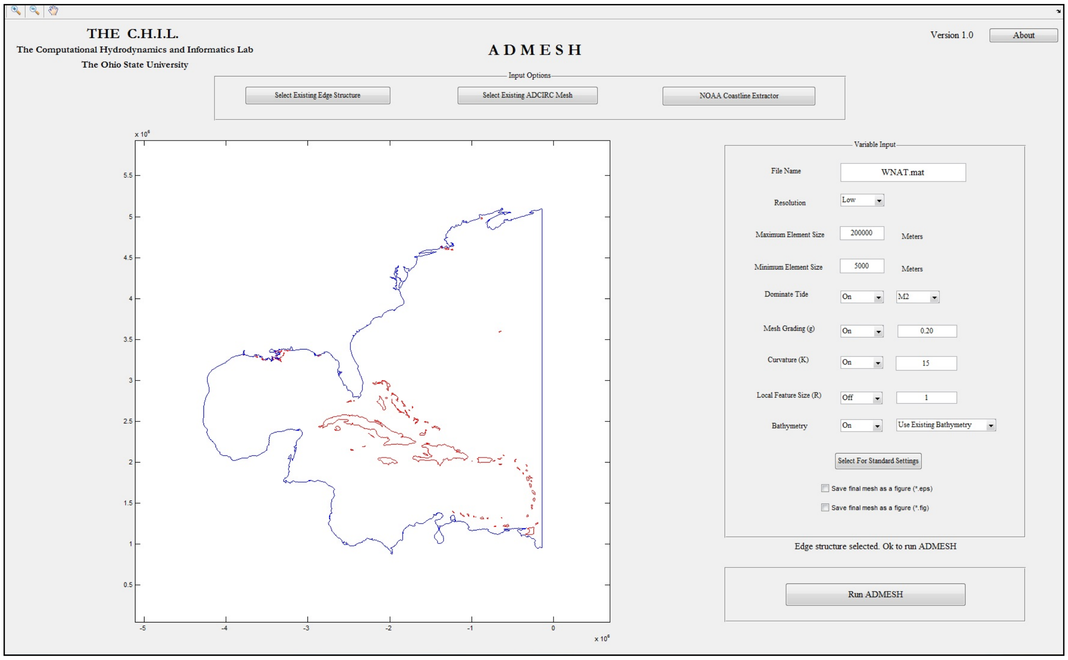


Figure 4.1: WNAT Coastline preview in the ADMESH GUI.

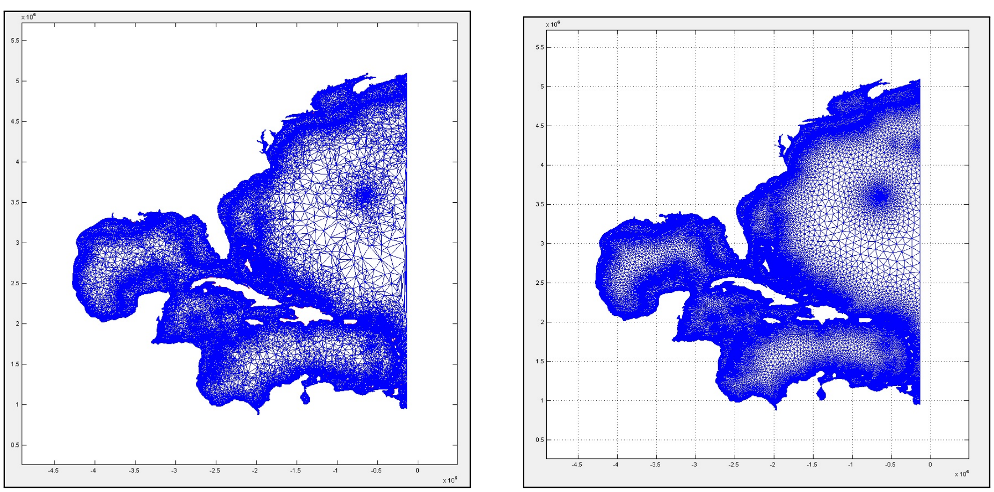


Figure 4.2: A mesh of the Western North Atlantic tidal (WNAT) domain created using Admesh showing the initial Delaunay triangulation of the domain (left) and the final mesh obtained from force equilibrium (right).

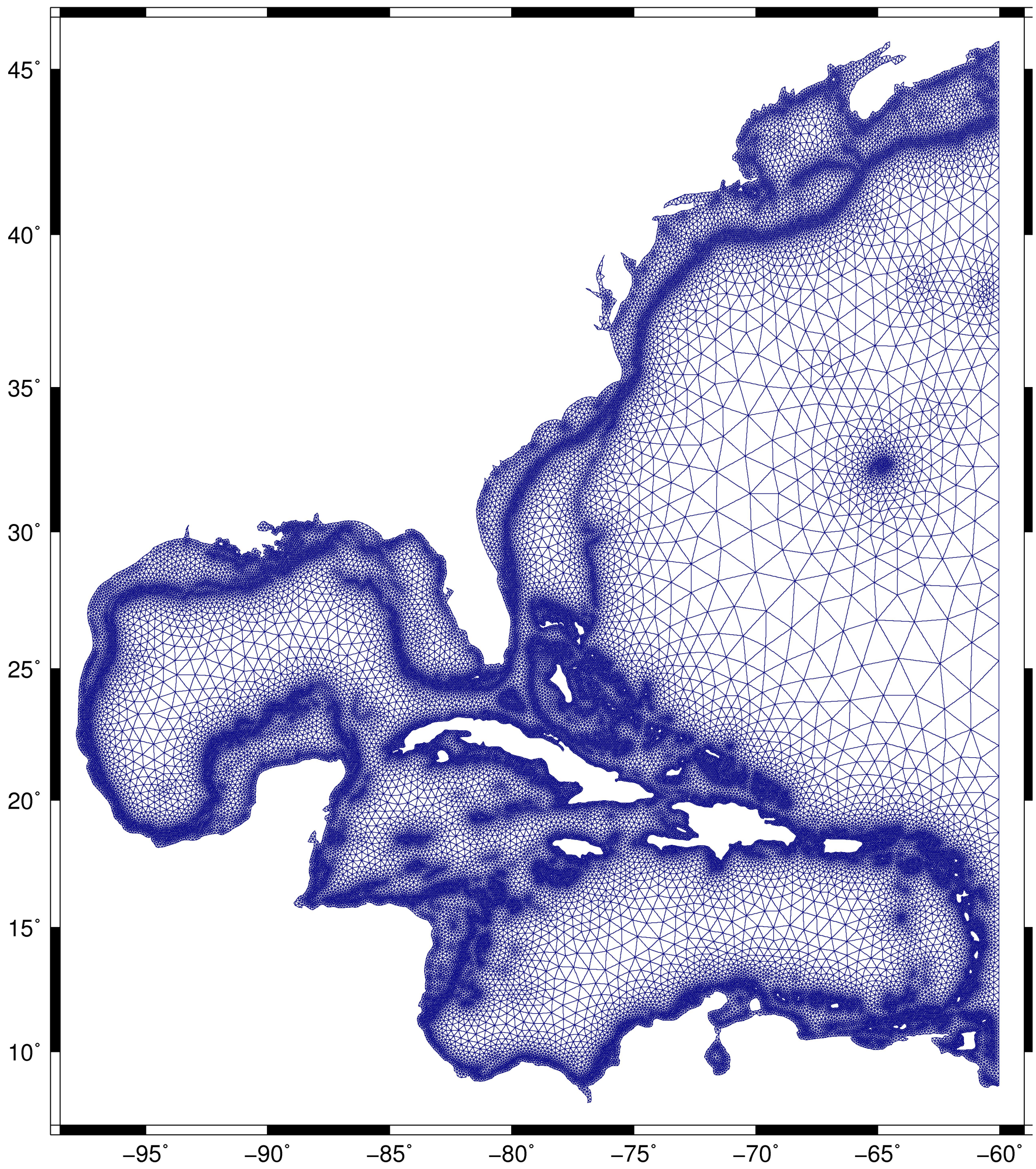


Figure 4.3: A completed mesh of the Western North Atlantic tidal (WNAT) domain automatically generated using Admesh.

4.2 The Gulf of Mexico

The Gulf of Mexico domain is an example of a higher resolution mesh compared to the WNAT example discussed previously. From Figure 4.5, it can be seen that a large number of elements provided near shore and along the shelf break. This domain, along with bathymetric data, was uploaded to ADMESH from an existing ADCIRC mesh. An unstructured mesh was generated with a medium resolution setting, a maximum element size of 50 km, a minimum element size of 200 m, a mesh grading factor of 0.20, and a curvature of 15. ADMESH completed the mesh in 7.04 hours and this example has an average mesh quality of 0.97.

Figure 4.4 shows the edge structure prior to running ADMESH. Figure 4.5 shows the final mesh obtained from force equilibrium and zoomed in areas of the mesh.

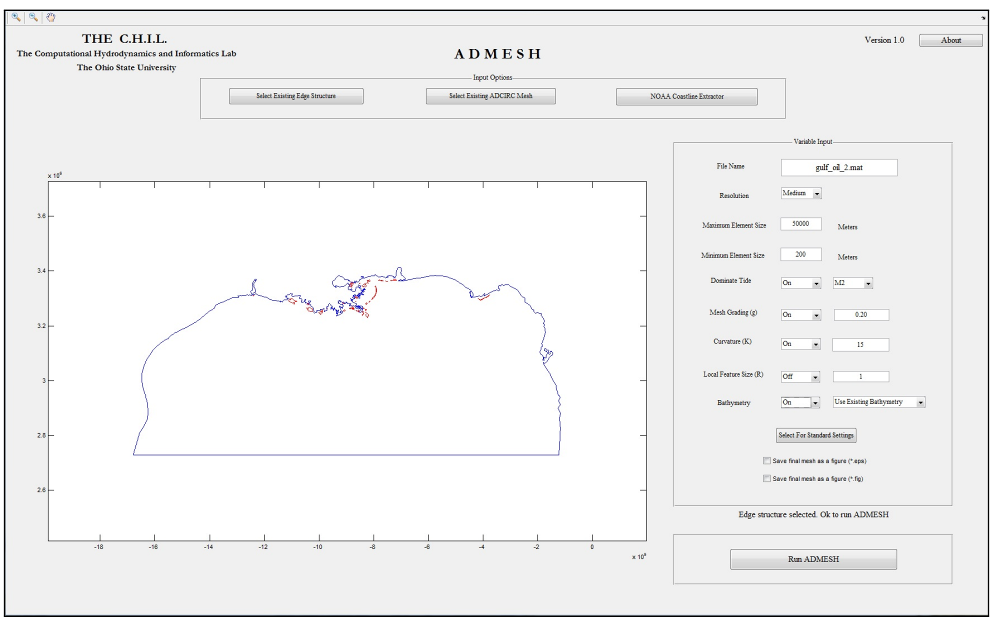


Figure 4.4: The Gulf of Mexico Coastline preview in the ADMESH GUI.

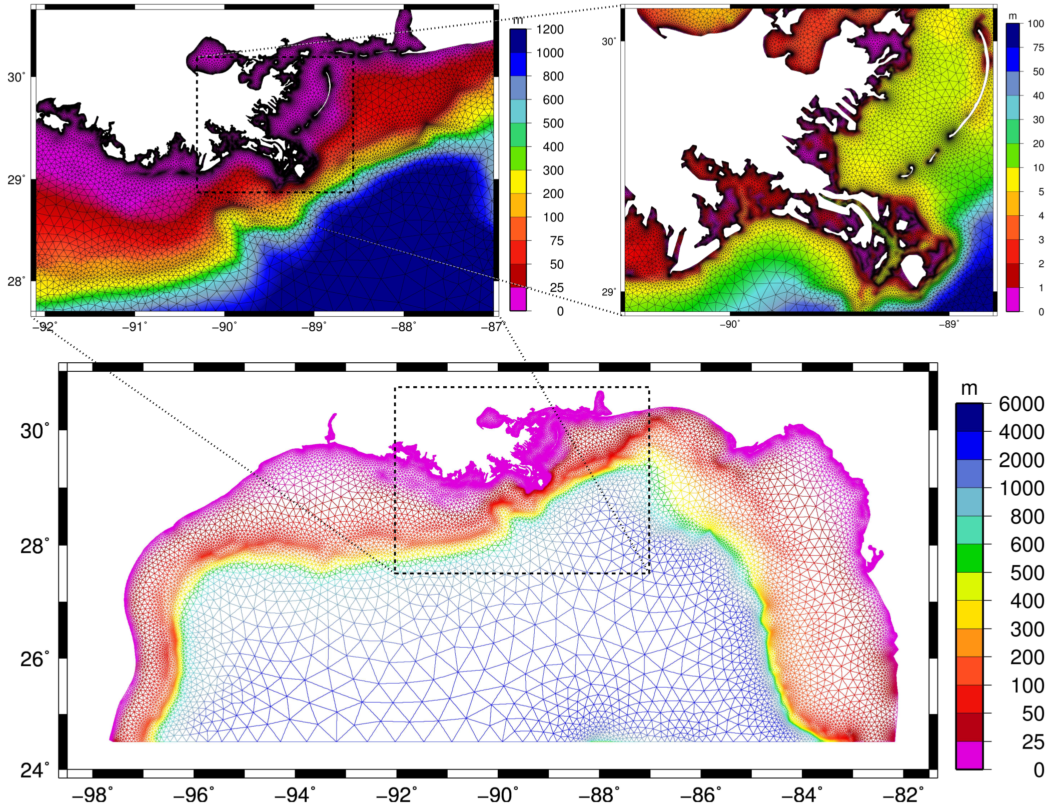


Figure 4.5: A mesh of the Gulf of Mexico automatically generated by ADMESH. Colorbars indicate bathymetric depth in meters (m).

4.3 Cape Cod, Massachusetts

The Cape Cod Bay mesh shown in Figure 4.7 is an example of ADMESH producing a computational mesh excluding bathymetry. This example indicates how ADMESH can create a high resolution mesh of an area with complex shorelines with minimal user input. In Figure 4.7, the close-up image of Little Pleasant Bay shows how ADMESH is able to provide appropriate resolution near the complex shore line. This domain was extracted using the NOAA Coastline Extractor. The unstructured mesh was generated with a low resolution setting, a maximum element size of 2 km, a minimum element size of 25 m, a mesh grading factor of 0.20, and a curvature of 15. ADMESH completed the mesh in 2.40 hours and this example has an average mesh quality of 0.93.

Figure 4.6 shows the edge structure prior to running ADMESH. Figure 4.7 shows the final mesh obtained from force equilibrium and zoomed in areas of the mesh.

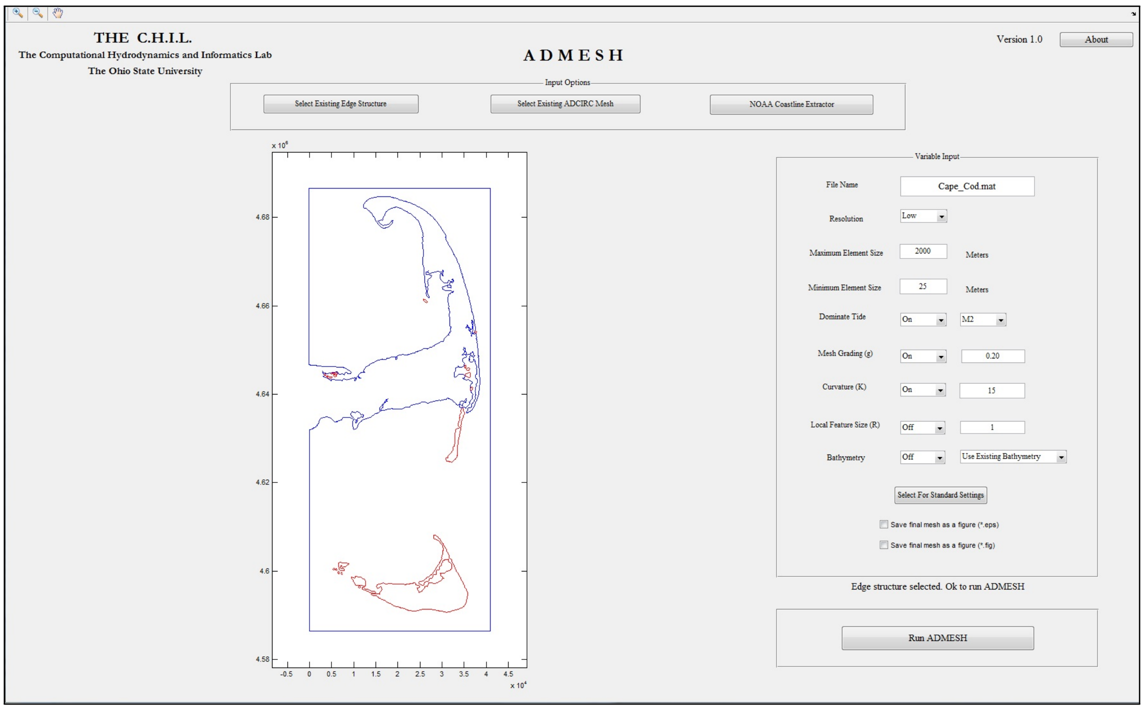


Figure 4.6: Cape Cod Bay Coastline preview in the ADMESH GUI.

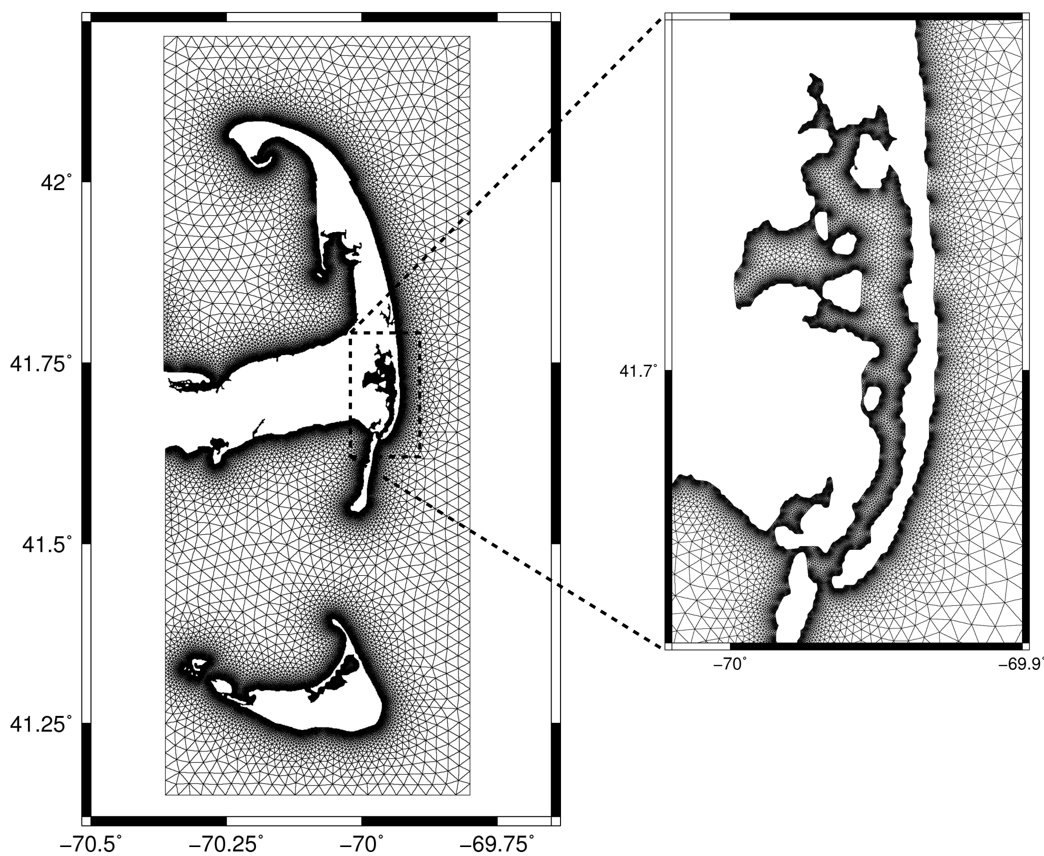


Figure 4.7: A mesh of Cape Cod automatically generated by Admesh, with the inset showing a close-up of Little Pleasant Bay.

4.4 Italy

Italy is another case that displays the ability for ADMESH to create a high resolution mesh with a complex domain excluding bathymetry. This domain was extracted using the NOAA Coastline Extractor. An unstructured mesh was generated with a low resolution setting, a maximum element size of 100 km, a minimum element size of 2.5 km, a mesh grading factor of 0.20, and a curvature of 15. ADMESH completed the mesh in approximately 9 minutes and this example has an average mesh quality of 0.93.

Figure 4.8 shows the edge structure prior to running ADMESH. Figure 4.7 shows the final mesh obtained from force equilibrium and zoomed in areas of the mesh.

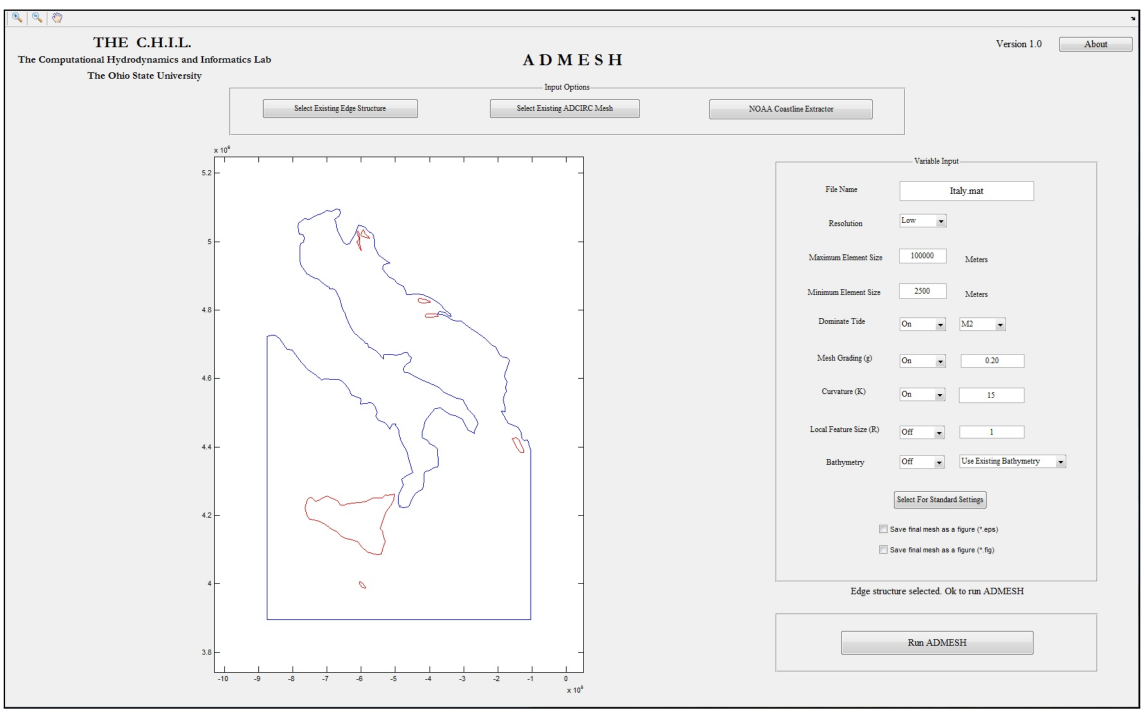


Figure 4.8: Italy Coastline preview in the ADMESH GUI.

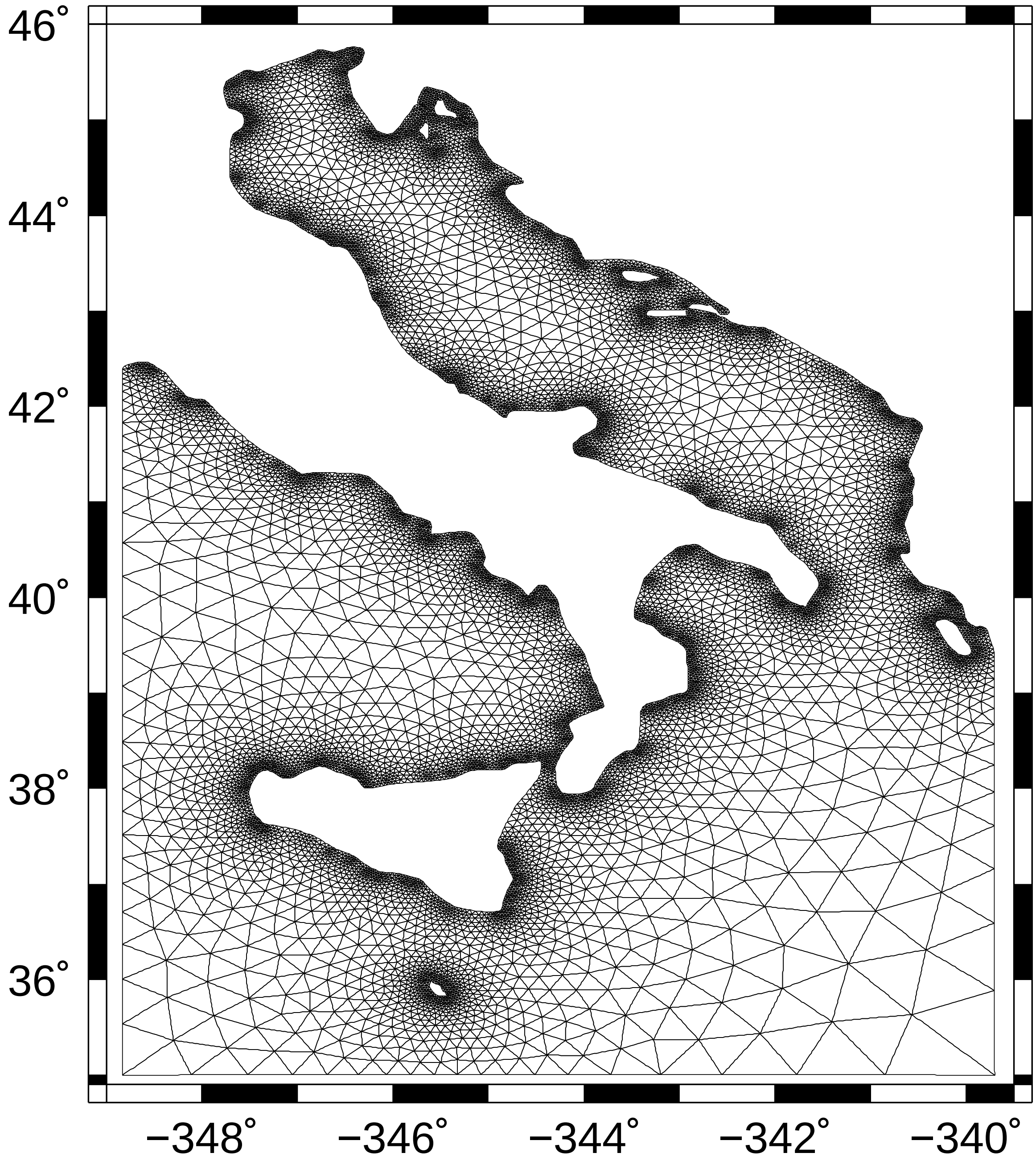


Figure 4.9: A mesh of Italy automatically generated by ADMESH.

CHAPTER 5

CONCLUSION AND FUTURE WORK

The ADMESH GUI addresses the challenge of generating a computational mesh of a domain of interest with respect to time and the user-intensive processes that are often involved in creating a mesh. Coupling the online NOAA Coastline Extractor tool with the GUI provides the user the option to select a domain of their choice to model. Another option for selecting a domain is allowing the user to upload an existing ADCIRC mesh. Following selection of a domain and performing error checks in the GUI, the ADMESH program automatically generates a computational mesh requiring minimal user input in the GUI and displaying the relevant output. The methods used in the ADMESH program ensure that the meshes produced are of high quality and possess the appropriate amount of resolution necessary throughout the domain for simulation. Element quality checks are done to provide feedback to the user on the quality of the overall mesh created. Finally, the ADMESH GUI can save ADCIRC readable files so the mesh can be used for simulation.

With regard to future development of the ADMESH GUI, there are several areas of the GUI that can be further developed to improve the reliability of the program, the speed of mesh generation, and the user interaction with the GUI. These areas are:

1. *Utilizing image segmentation software*: The NOAA Coastline Extractor has demonstrated the usefulness of user-defined boundaries for modelling. However, limitations exist in the current program and the availability of worldwide coastline data. Currently, the NOAA Coastline Extractor will only allow the user to select a domain with two endpoints, for example, Figure 3.3 and Figure 3.4 displays these limitations. Also, accuracy of worldwide coastline data can vary. It would be useful for the user to be able to select a domain from any location that may require multiple domains to be linked by the user. Enabling the user to extract coastlines from satellite images or Google Earth would be extremely beneficial. Therefore, further development for this area will involve coupling the ADMESH GUI with image segmentation software.

2. *Reducing the computational limitations of ADMESH*: In ADMESH, automatic generation of a computational mesh for larger domains requiring very high resolution can still be a time consuming process. Future development in this are will focus on the following:

   - *Incorporating FORTRAN MEX-files into the ADMESH program*: Currently, all ADMESH function files are coded in MATLAB and FORTRAN. FORTRAN is commonly used in numerical coding for faster processing and therefore is potentially very beneficial for the ADMESH project. MATLAB is capable of calling on FORTAN files by using MEX-files [17]. This could potentially provide quicker results from the ADMESH program while still being able to utilize MATLAB's graphical user interface design environment (GUIDE).

- *Parallelization*: Parallel computing is an optimization technique where many calculations are carried out simultaneously in turn resulting in reduced execution time. Parallelization will be investigated with ADMESH using MATLAB's parallel computing toolbox as another means for reducing computational time when generating a large high resolution computational mesh.

- *GPU Computing*: Another method for reducing computational time that will be investigated is the use of a graphics processing unit (GPU) to perform computations that would normally be handled by the central processing unit (CPU). MATLAB also includes GPU computing in it's parallel computing toolbox. A GPU is a programmable chip that is originally intended for graphics. However, GPU's have a highly parallel structure that makes them more effective at processing larger blocks of data in parallel than general purpose CPU's [18].

3. *Coupling ADMESH with ADCIRC* : The next major restructuring of the ADMESH GUI will incorporate the ADCIRC program to produce an all in one software package. The latest design of the ADMESH/ADCIRC GUI is shown in Figure 5.1. The GUI in development will consist of tabs aligned at the top of the GUI that will correspond to different features for modeling (i.e., ADMESH, coastline extractor, ADCIRC, ADVIEW (new video viewing window), etc.).

These future developments would enable the user to download a domain of their choice, produce a highly quality computational mesh of the domain, and perform storm surge or tidal simulation using one software package that involves minimal user interaction.

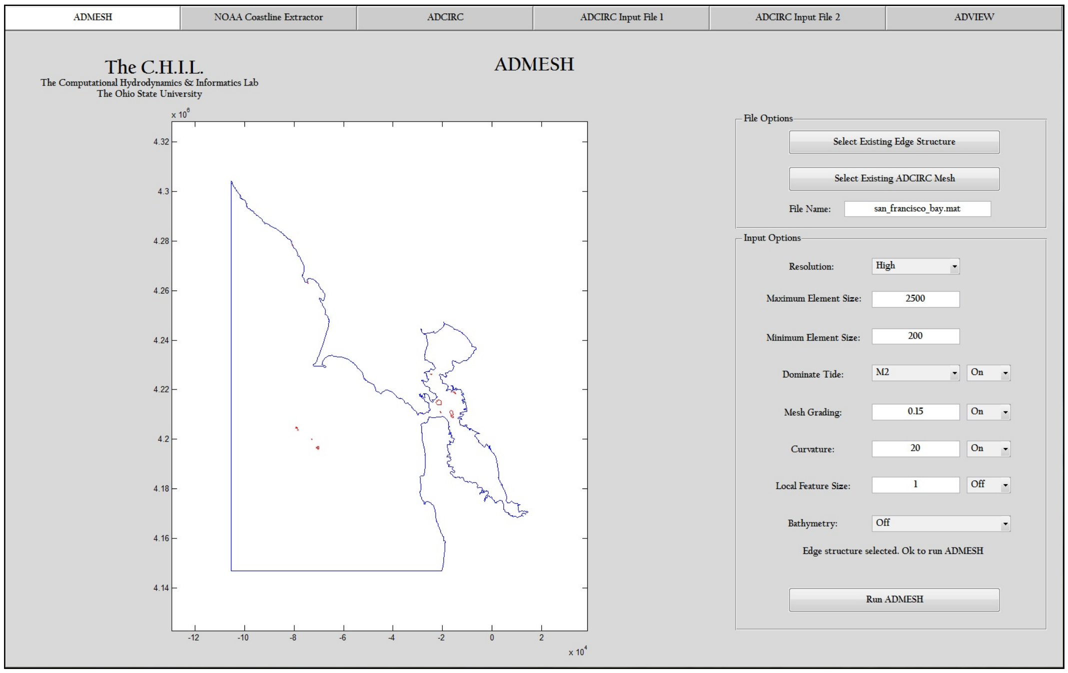


Figure 5.1: Future ADMESH GUI layout.

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